Two Photon HBT and the study of direct photons at RHIC II

1) The "point" (message) of this talk.

2) The basic idea: No HBT for γ's from π^0 decay.

3) Some theoretical motivations

4) Coneptual experiment and simulations

5) Conclusions

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Bar Harbor
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Acknowledgements

Alexei Chikanian (did all the work!)

Helen Caines (HBT consultant)

The point-message of this presentation:

The study of HBT correlations opens a new window on the study of the QGP.

Photons are directly emmited by the QGP (unlike hadrons)

The direct γ spectrum and HBT correlations allow studies of the QGP (Temp., Size, duration) that define its characteristics in ways that no other measurements can do!

Although "NOT EASY", an upgraded STAR at RHIC II can carry out these studies.

It would be a unique and definitive program.

Basic Idea

The key point of this work is that the presence of an intensity interferometric peak (HBT) in $C(q_{inv})$ (or its elaborations, for q_{out}, q_{side}, etc.) can only happen for direct γ's NOT for γ's from π^0 or η.

Note: π^0 lifetime $= 8.4 \times 10^{-17}$ sec.

$$c\tau = 2.5 \times 10^{-6}\ \text{cm} = 2.5 \times 10^{7}\ \text{Fermi}$$

this would give a peak "inside" $q_{inv} \cong 8\ \mu$volts (!)

η width $\Gamma = 1.2$ KeV

$$\Delta\omega\,\Delta\tau \sim 1$$

$$\frac{\Delta E}{\hbar}\,\Delta\tau \sim 1$$

$$\Delta\tau \sim \tau = 5.5 \times 10^{-19}\ \text{sec}$$

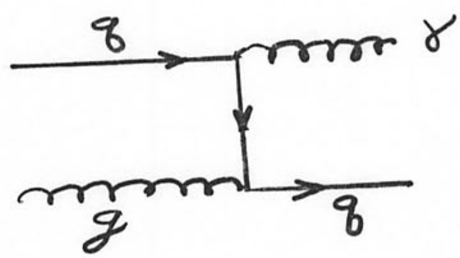
$$c\tau = 1.64 \times 10^{5}\ \text{Fermi}$$

q_{inv} peak inside .001 eV (!)

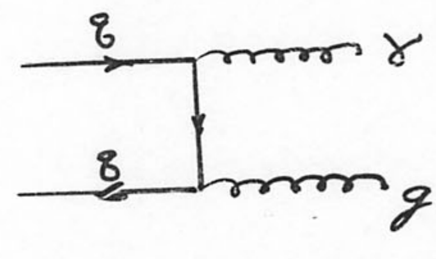
"Direct" Photons

The emission of electromagnetic energy from the collision of high energy heavy ions has long been identified as one of the observables capable of casting light on the nature of the system produced in the collision.

When the system is in a "partonic" state, the two processes which are important are:



"QCD Compton"



"QCD Annihilation"

The emitted γ's do <u>not</u> come into thermal equilibrium with each other as their interaction MFP is too long. (Kapusta, Lichard, and Siebert PRD **44**, 2774 (91))

Rather, the photon spectrum reflects the temperature of the quarks and gluons in the partonic state.

The theoretical calculation of the direct photon spectrum must average over the "partonic" spectrum and must take flow phenomena into account. Also, direct γ from hadronic stage

This is not the place to elaborate on the theory but for reference we show a calculation of P.V. Ruuskanen (Nucl. Phys. A544, 169c (92))

The relevant result for the following is the ratio of direct γ's to γ's from π^0 decay.

From Ruuskanen $\dfrac{\gamma_{direct}}{\gamma_{\pi^0}} \sim \dfrac{1}{20} \rightarrow \dfrac{1}{50}$

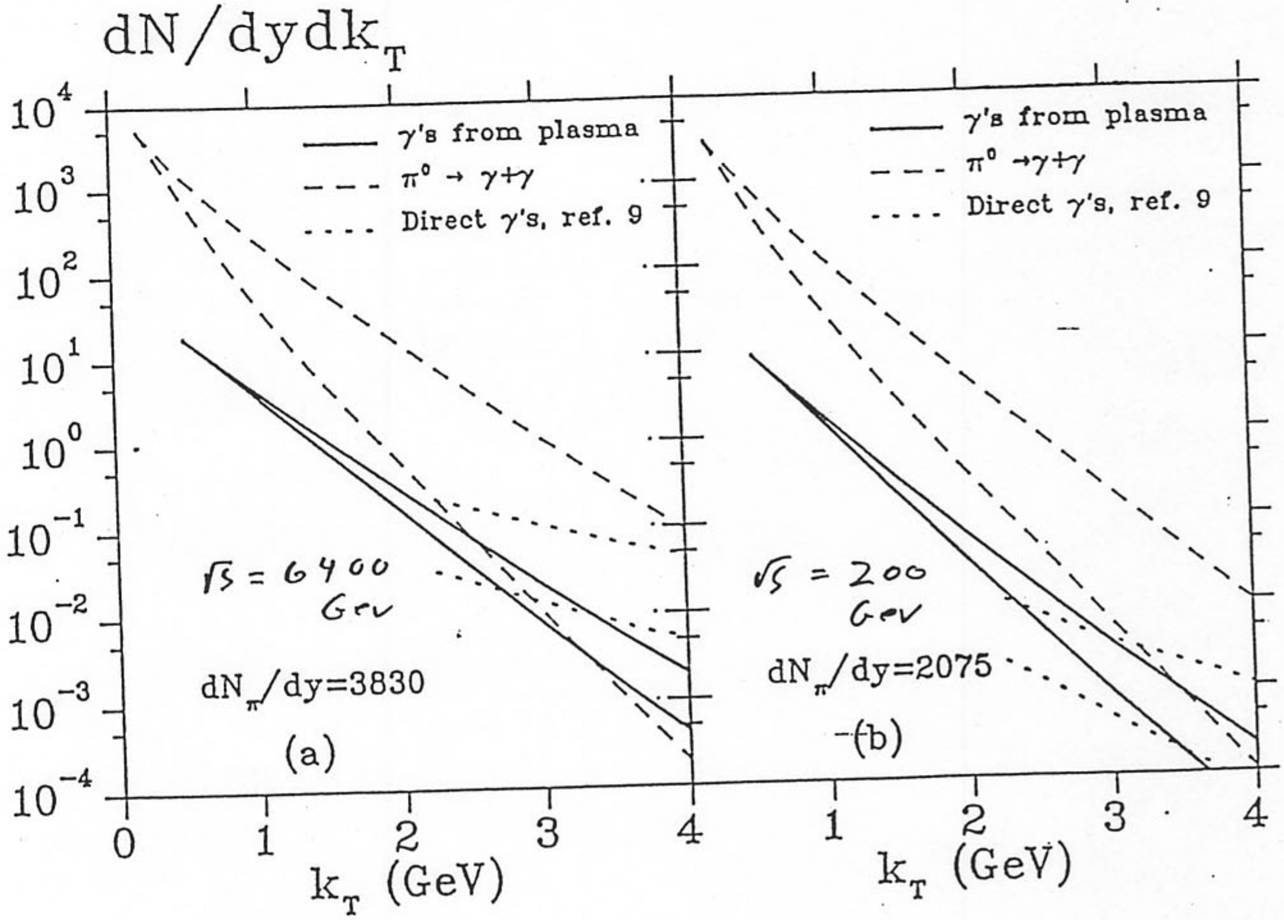


Figure 6. Transverse momentum spectra of real photons in Pb+Pb collisions. In (a) the thermal spectrum is calculated with $dN_\pi/dy = 3830$ and the Drell–Yan spectrum at $\sqrt{s} = 6400$ GeV. In (b) $dN_\pi/dy = 2075$ and $\sqrt{s} = 200$ GeV.

"Qualitative" Analysis

(Wong, ch. 16)

Neglecting Flow ...

QGP: $$E_\gamma \frac{dN_\gamma}{d\vec{p}_\gamma} \sim f_q(\vec{p}_\gamma) \sim \exp\left[-\frac{E_\gamma}{T_q}\right]$$

Hadron Gas : $$E_\gamma \frac{dN_\gamma}{d\vec{p}_\gamma} \sim f_\pi(\vec{p}_\gamma) \sim \exp\left[-\frac{E_\gamma}{T_\pi}\right]$$

Quark Temp, T_q, in QGP

should be higher than hadron

gas Temp T_π.

Obviously full analysis needs to be done - but discriminating power is there. Needs Flow, Bjorken expansion ...

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Two-photon correlations: from Young experiments to heavy-ion collision dynamics

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Contents

Abstract

Two-photon correlations are discussed within the formalism of Hanbury-Brown and Twiss interferometry and Bose–Einstein correlations. The technique is presented as a universal tool to study the properties of any boson source – light sources such as stars, or photon and meson sources in the early phase of heavy-ion collisions. The formalism is developed starting from optics and quantum statistics and is finally adapted to the dynamics of heavy-ion collisions. Emphasis is put on the experimental methods derived to display the interference between photons from nuclear reactions. The influence of one-dimensional projections and the detector response on the interpretation of the source properties are discussed. The method is illustrated using experimental data, available only in the intermediate (several tens of A MeV) energy domain. The observed interference signal is interpreted, guided by dynamical phase-space calculations, in terms of source size and reaction dynamics. It is found that photons are emitted as brief light flashes, the relative intensity of which can be linked via model calculations to the incompressibility modulus of nuclear matter. At ultrarelativistic energies, two-photon correlations are presented as a tool to observe the phase transition towards the quark–gluon plasma.

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denominator of the correlation function, of prime importance for the extraction of reliable source parameters.

The results obtained with the photon spectrometer TAPS have unambiguously demonstrated the existence of the interference between bremsstrahlung photons. The interpretation of the source parameters extracted revealed a source distribution more complex than the expected overlap zone between the colliding nuclei. The interferometry measurements confirm the conclusions of the study, guided by dynamical phase-space calculations, of single-photon production. The nuclear reaction generates, under certain conditions, a density oscillation of the di-nuclear system. During each compression phase photons are emitted, most intensively during the first compression, further emissions diminishing in intensity. A source distribution with two components, direct and thermal bremsstrahlung-photons, separated in space–time provided a good description of the experimental correlation functions, as well as of their dependence with several parameters of the reaction. This interpretation allowed to extract the spatial source-extent and the relative intensity of both direct and thermal photon emission. The latter being related to the strength of the recompression provides a measure of the incompressibility modulus of infinite nuclear matter.

The photon-source distribution generated by dynamical phase-space calculations was used to construct the correlation function assuming that both photons in the pair were emitted independently. The results provided a satisfactory agreement with the data. However, the absence of the modulation measured for one of the systems led to the study of the sensitivity of the correlation function to the structure of the recompression phase. The best agreement with the data was obtained for the expected scenario where the di-nuclear system fragments into PLF and TLF after the initial compression. This study confirms the power of the technique to probe the collision dynamics as well as the need of improved sets of data, which will be soon provided by new experiments.

Although this review focused on the issues encountered in heavy-ion collisions at intermediate energies, the same arguments can be used to exploit the two-photon correlation technique in heavy-ion collisions at ultrarelativistic energies. There too most energetic photons are produced in the early phase of the nuclear reaction, only the energy of the photons being larger by about two orders of magnitude. Photons again represent a unique probe because of their weak interaction with the nuclear medium. If a deconfinement phase of quarks and gluons is formed, energetic photons will be emitted in parton collisions. They will compete with photons emitted during the hadronic phase at a later stage of the reaction, when the system expands. We face again the presence of two photon sources which can be revealed in a unique way by studying the two-photon correlation function. At such high energies the experimental difficulties are also considerably increased, mainly for the identification of direct photons of interest among the overwhelming contribution of photons stemming from the decay of neutral mesons. This partly explains why no data are available yet. But the effort put in this programme by the WA80/98 collaboration is fully justified, as are the plans to continue these studies at RHIC and LHC.

Two-photon correlations can be considered as a universal tool which originated in optics but finds application in astronomy as well as in nuclear physics, at both intermediate and ultrarelativistic energies. In heavy-ion physics this technique has no counterpart to access original information on the early phase of the nuclear reaction, the most interesting phase in terms of baryonic and energy densities. At intermediate energies information on the EOS of nuclear matter has been already extracted, and more is expected from future experiments. At ultrarelativistic energies

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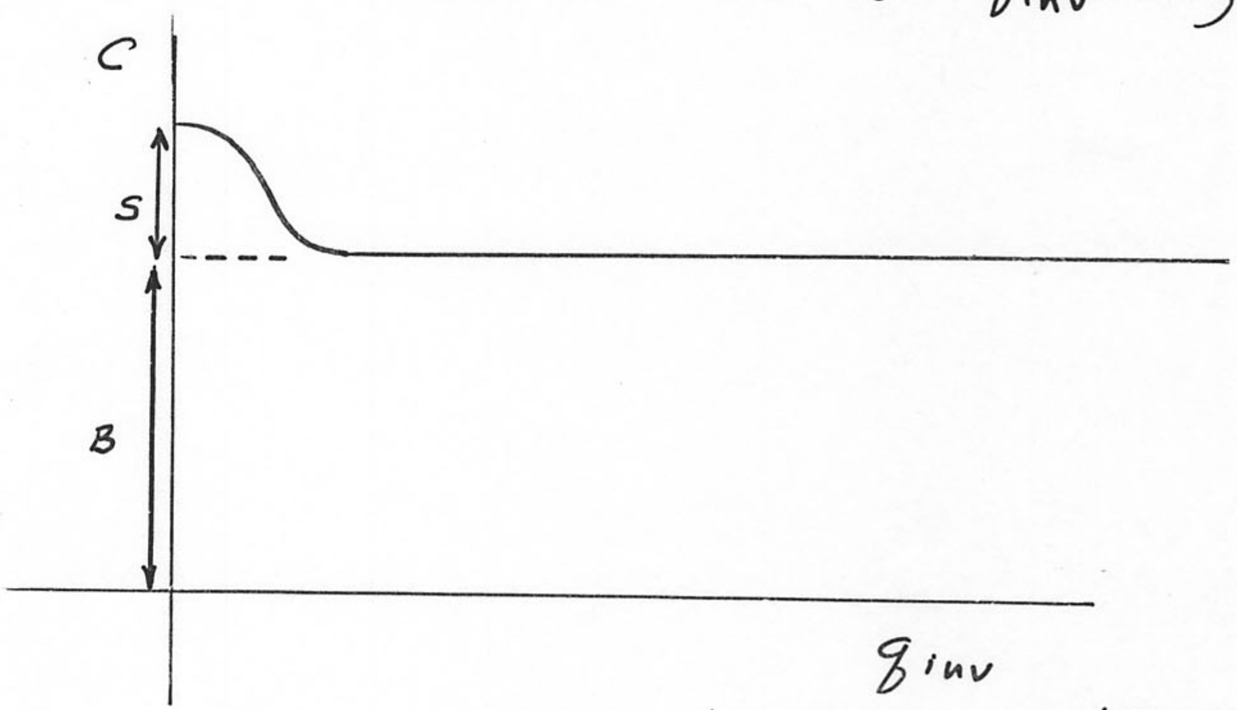
Furthermore, it is widely believed that the direct γ's are emitted in an incoherent fashion (so HBT $\lambda = 1$). [Although this point could probably bear further thought]

With this assumption, the "HBT" peak can be converted to a direct photon spectrum.
(Corr. Function $C = 1.5$ at $q_{inv} = 0$).



$$\frac{S}{B} = .5 \ \frac{\#\text{ Direct } \gamma \text{ pairs}}{\#\text{ all } \gamma \text{ pairs}} = .5 \ \frac{(\text{Flux } d.\gamma)^2}{(\text{Flux all } \gamma)^2}$$

$$\boxed{\text{Flux of Direct } \gamma = \sqrt{2\frac{S}{B}} \ \text{Flux all } \gamma}$$

Conceptual Experiment

Design Philosophy

Choose a conceptual detector design - probably overkill

1) Tune up simulation Software

2) Establish "baseline" for comparison with more realistic detectors

3) Establish a "proof of principle" for the study of direct γ HBT

Resolution

Can get a "ballpark" understanding from the formula:

$$q_{INV}^2 = 2E_1E_2(1-\cos\theta)$$

E_1, E_2 are γ energies
θ is included angle

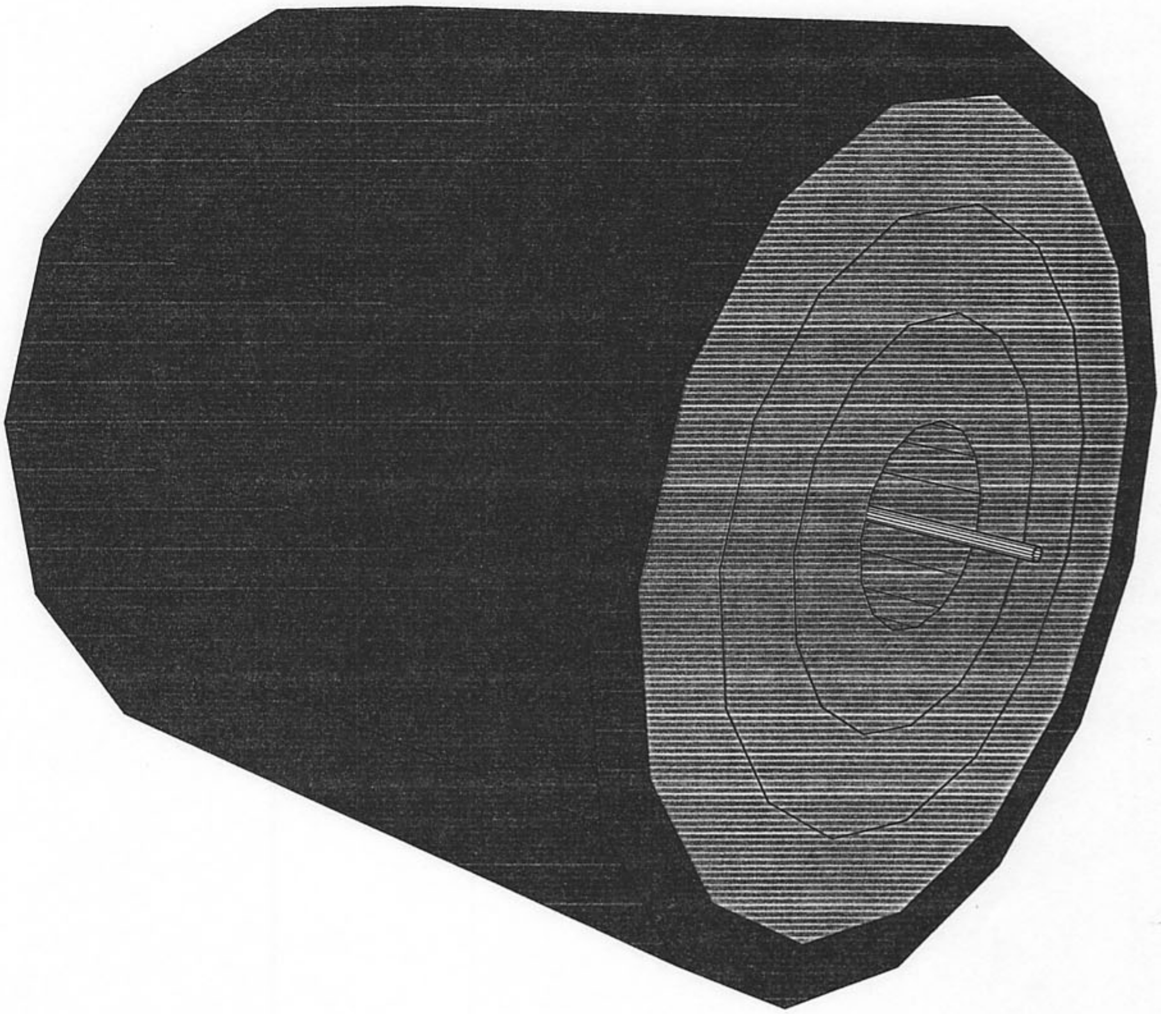
For $E_1, E_2 \sim 1\,\text{GeV}$, $\Delta q_{IN} \sim 10\,\text{MeV/c}$
one needs good
angular resolution

$$\Delta\theta \lesssim 0.5^\circ$$

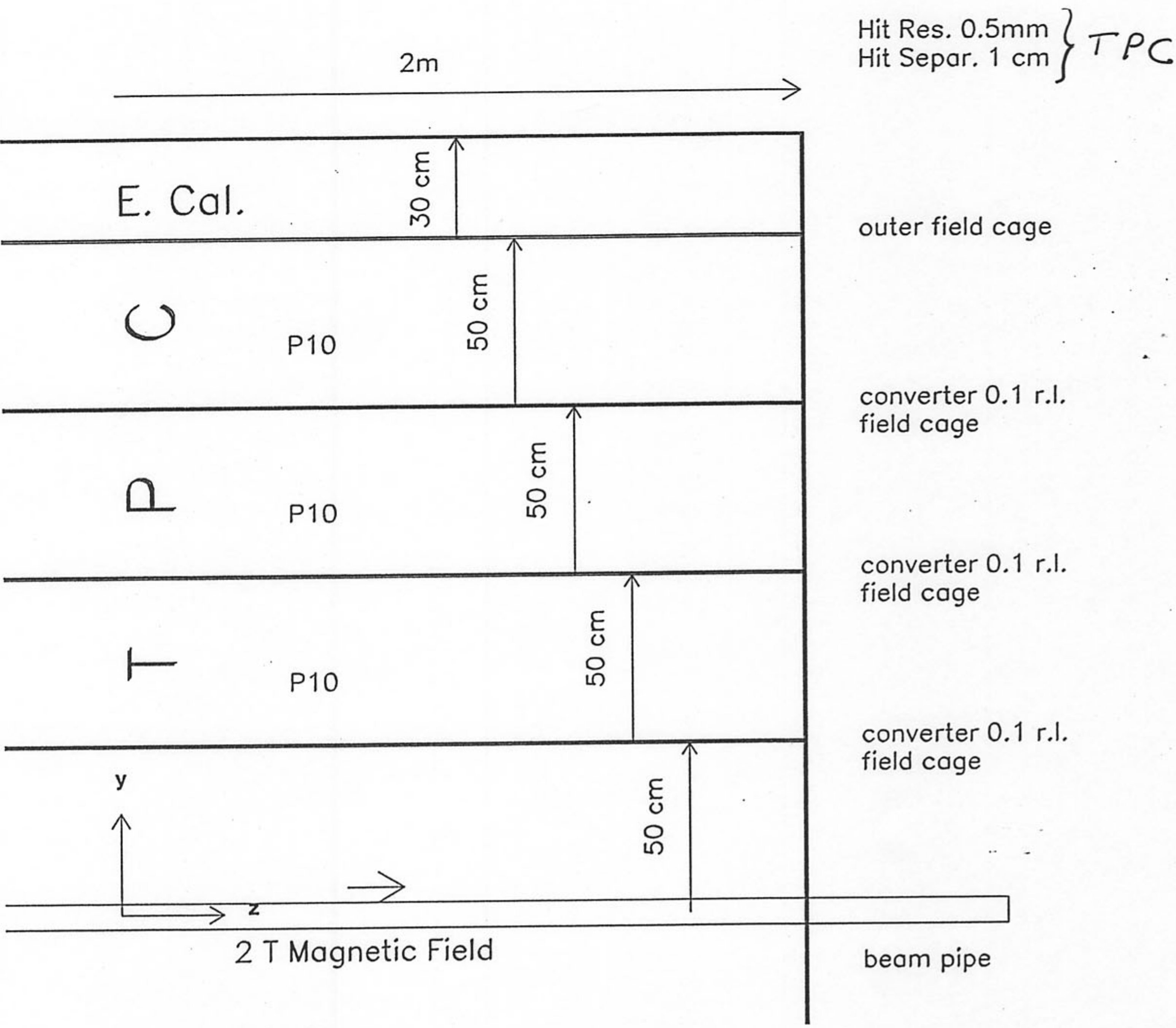
"Modest" momentum resolution

$$\frac{\Delta P}{P} = \frac{\Delta E}{E} \sim 10\%$$

These just "set the stage", need good Simulation to determine optimum detector design.



Conceptual T P C & E.Cal. for Direct γ experiment



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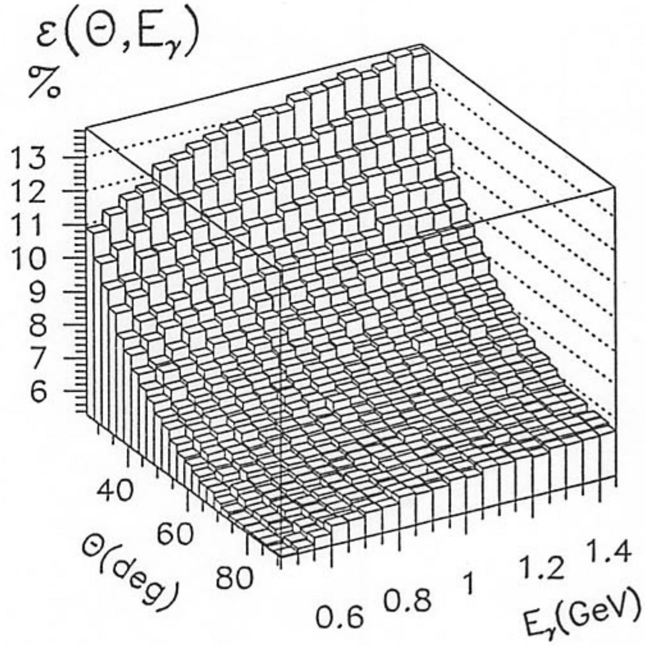
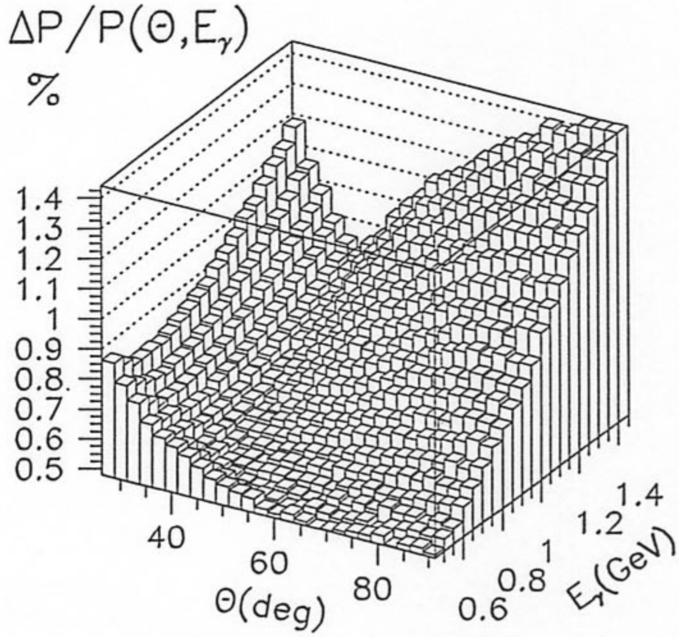
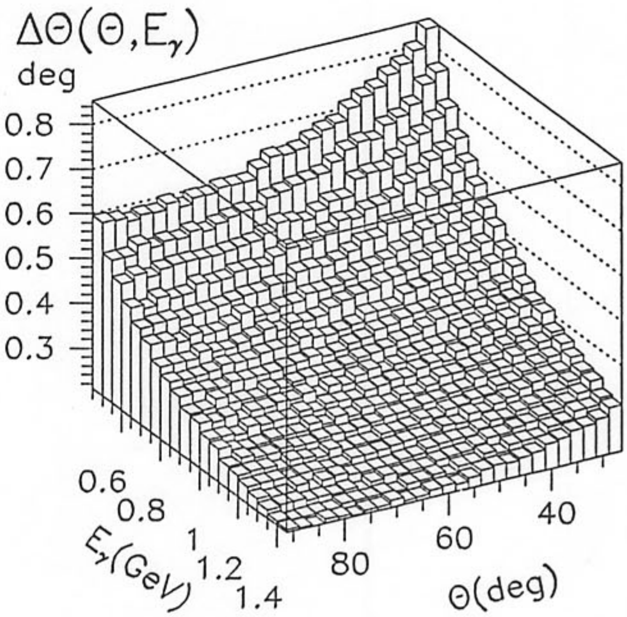
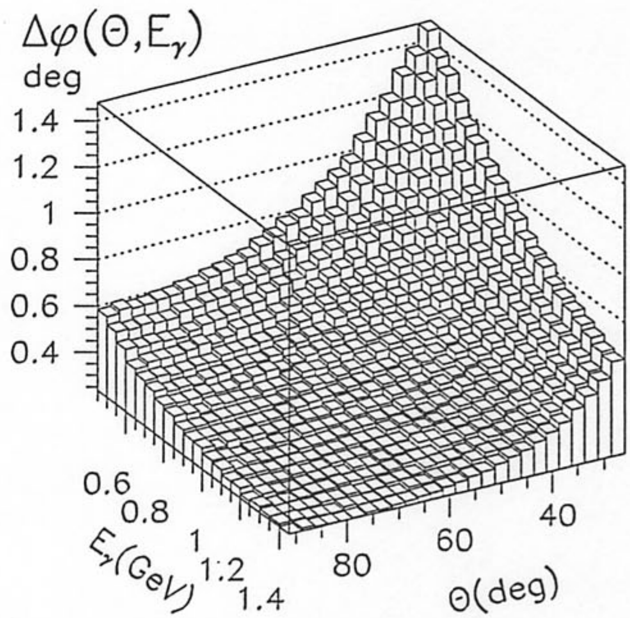
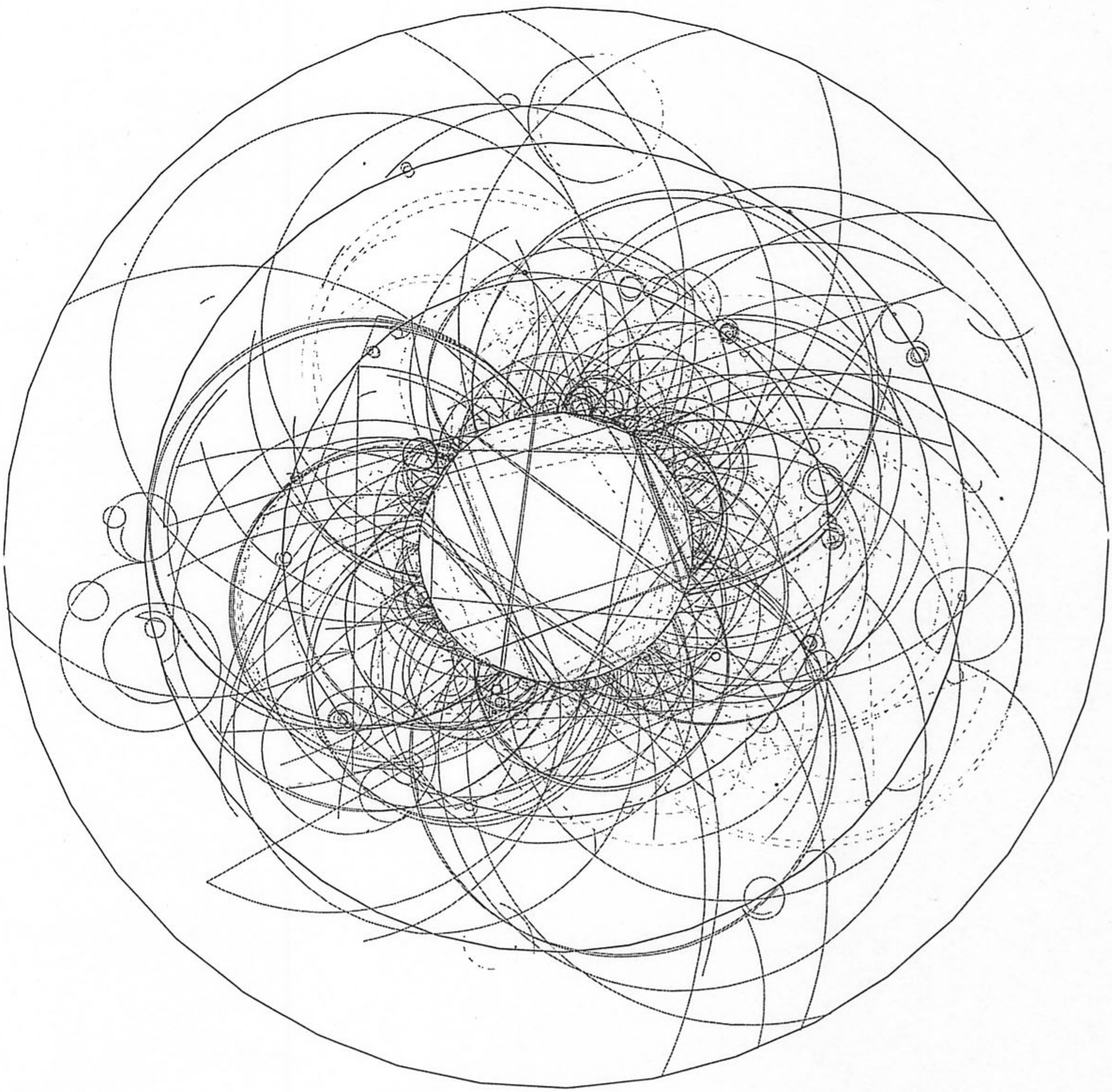


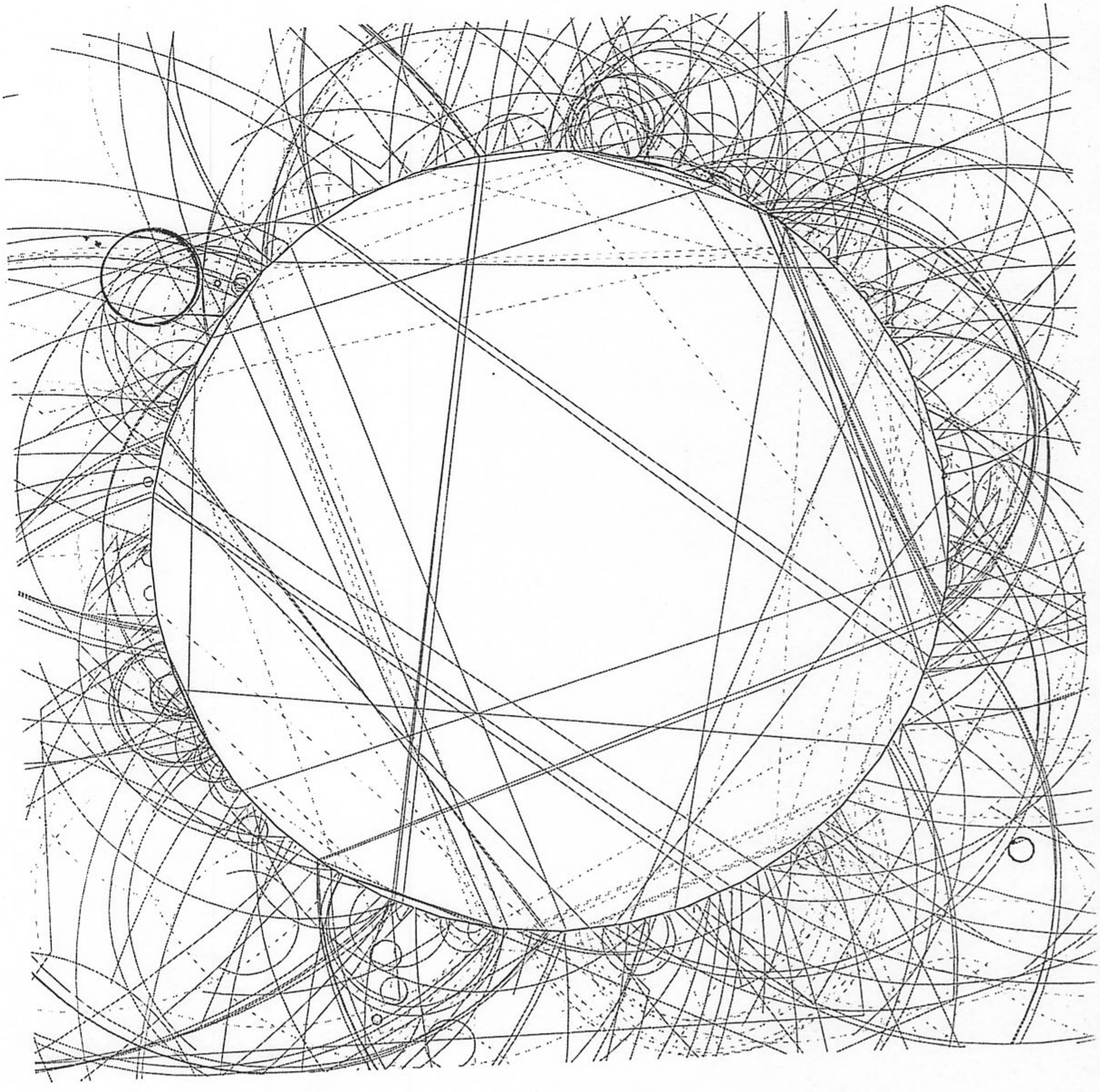








1 HIJING EVENT
$\Delta Z = 10cm$
$Z = 0$



1 HIJING EVENT
$\Delta z = 10$ cm
$z = 0$

Simulation

1) Direct γ Spectrum a la Boyanovsky
(This is $\frac{\gamma_d}{\gamma_{\pi^0}} \simeq \frac{1}{85}$), $T_{QGP} = 300$ MeV

2) Pairs used

TPC - TPC
TPC - Calorimeter

3) Calorimeter Assumptions

minimum separation between accepted γ = 3 cm

$$\frac{\Delta E}{E} = \frac{10\%}{\sqrt{E}}$$

$$\Delta\theta = 7.5 \text{ mr}$$

$$\text{Eff.} = .9$$

4) π^0 γ spectrum from HIJING
(in "long" run only γ's)
central events.

Direct photons: A nonequilibrium signal of the expanding quark-gluon plasma at RHIC energies

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(January 22, 2001)

Direct photon production from a longitudinally expanding quark-gluon plasma (QGP) at Relativistic Heavy Ion Collider (RHIC) energies is studied with a real-time kinetic description that is consistently incorporated with hydrodynamics. Within Bjorken's hydrodynamical model, energy nonconserving (anti)quark bremsstrahlung $q(\bar{q}) \to q(\bar{q})\gamma$ and quark-antiquark annihilation $q\bar{q} \to \gamma$ are shown to be the dominant nonequilibrium effects during the transient lifetime of the QGP. For central Au+Au collisions at RHIC energies $\sqrt{s} \sim 200A$ GeV, we find a significant excess of direct photons in the range of transverse momentum $p_T \gtrsim 1.0 - 1.5$ GeV/c as compared to equilibrium results. The transverse momentum distribution at midrapidity falls off with a *power law* $p_T^{-\nu}$ with $2.5 \lesssim \nu \lesssim 3.0$ as a consequence of these off-shell processes, providing a distinct experimental *nonequilibrium signature*. The rapidity distribution is fairly flat in the interval $|y| \lesssim 2$. The power law exponent ν increases with the initial temperature of the QGP and therefore with the total multiplicity rapidity distribution dN_π/dy.

PACS numbers: 25.75.-q, 12.38.Mh, 13.85.Qk, 11.10.Wx

I. INTRODUCTION

The first observation of direct photon production in ultrarelativistic heavy ion collisions has been reported recently by the CERN WA98 collaboration in ^{208}Pb+^{208}Pb collisions at $\sqrt{s} = 158A$ GeV at the Super Proton Synchrotron (SPS) [1]. Most interestingly, a clear excess of direct photons above the background photons predicted from hadronic decays is observed in the range of transverse momentum $p_T > 1.5$ GeV/c in central collisions. As compared to proton-induced results at similar incident energy, the transverse momentum distribution of direct photons shows excess direct photon production in central collisions beyond that expected from proton-induced reactions. These findings indicate not only the experimental feasibility of using direct photons as a signature of the long-sought quark-gluon plasma (QGP) [2] but also a deeper conceptual understanding of direct photon production in ultrarelativistic heavy ion collisions.

Unlike many other new phases of matter created in the laboratory, the formation and evolution of the QGP in ultrarelativistic heavy ion collisions is inherently a nonequilibrium phenomena [3,4].

Currently, it is theoretically accepted that parton-parton scatterings thermalize quarks and gluons on a time scale of about 1 fm/c after which the plasma undergoes hydrodynamic expansion and cools adiabatically down to the quark-hadron phase transition. If the transition is first order, quarks, gluons, and hadrons coexist in a mixed phase, which after hadronization evolves until freeze-out. Estimates based on energy deposited in the central collision region at the BNL Relativistic Heavy Ion Collider (RHIC) energies $\sqrt{s} \sim 200A$ GeV suggest that the lifetime of the deconfined QGP phase is of order 10 fm/c with an overall freeze-out time of order 100 fm/c. Different types of signatures are proposed for each different phase.

Of all the potential signatures of a QGP [5], direct photons and dileptons emitted by the QGP, i.e., electromagnetic probes, are free of hadronic final state interactions and can provide a clean signature of the early stages of a thermalized plasma of quarks and gluons. Therefore a substantial effort has been devoted to a theoretical assessment of the spectra of direct photons and dileptons emitted from the QGP [6–12].

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"pessimistic" for

E_γ .5 → 1.4 GeV

($\frac{\text{Dir.}\,\gamma}{\pi^0\gamma} \sim \frac{1}{85}$)

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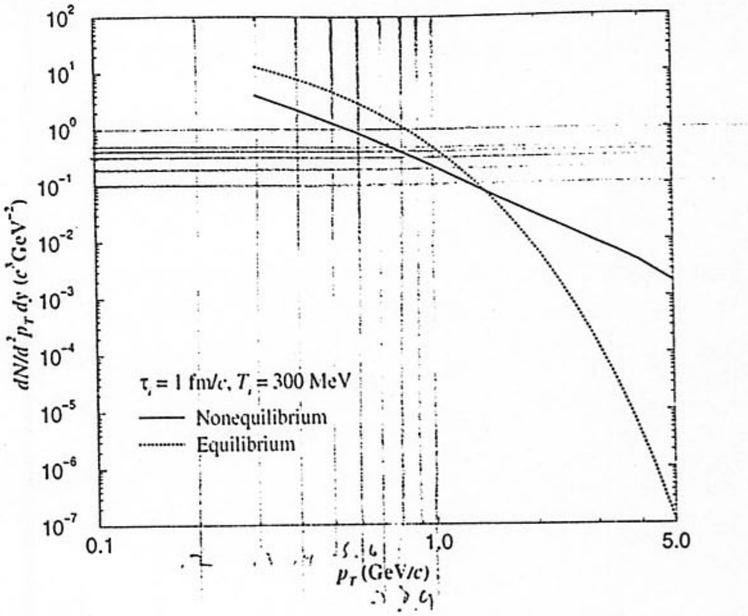


FIG. 3. Comparison of nonequilibrium (solid) and equilibrium (dashed) photon yields at midrapidity ($y = 0$) from a longitudinally expanding QGP with initial conditions $\tau_i = 1$ fm/c and $T_i = 300$ MeV.

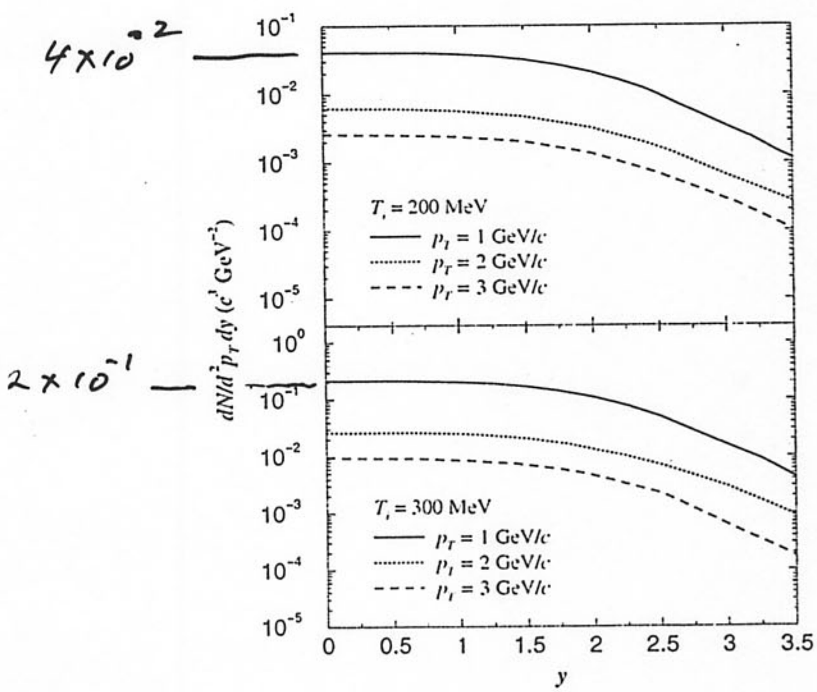


FIG. 4. Rapidity distribution of the nonequilibrium photon yield at $p_T = 1$ (solid), 2 (dotted), and 3 (dashed) GeV for a longitudinal expanding QGP with initial conditions $\tau_i = 1\,\mathrm{fm}/c$, and $T_i = 200$ (top) and 300 (bottom) MeV. The distribution is symmetric at $y = 0$.

200 Million Events

"Usual" Long. Comoving Coord. Syst. *

Parameters of 3d – correlation function

$$C - 1 = \lambda * \exp(-Q_{out}R_{out} - Q_{side}R_{side} - Q_{long}R_{long}) + \alpha$$

	Covar. matrix (norm.)			
$\lambda = (3.57 \pm 0.29)E{-3}$	0.521	0.580	0.466	0.069
$R_{out} = (9.26 \pm 0.63)$ fm		0.251	0.171	0.201
$R_{side} = (5.42 \pm 0.47)$ fm			0.194	0.222
$R_{long} = (6.05 \pm 0.42)$ fm				0.177
$\alpha = (0.48 \pm 0.18)E{-4}$				

* To save computer time

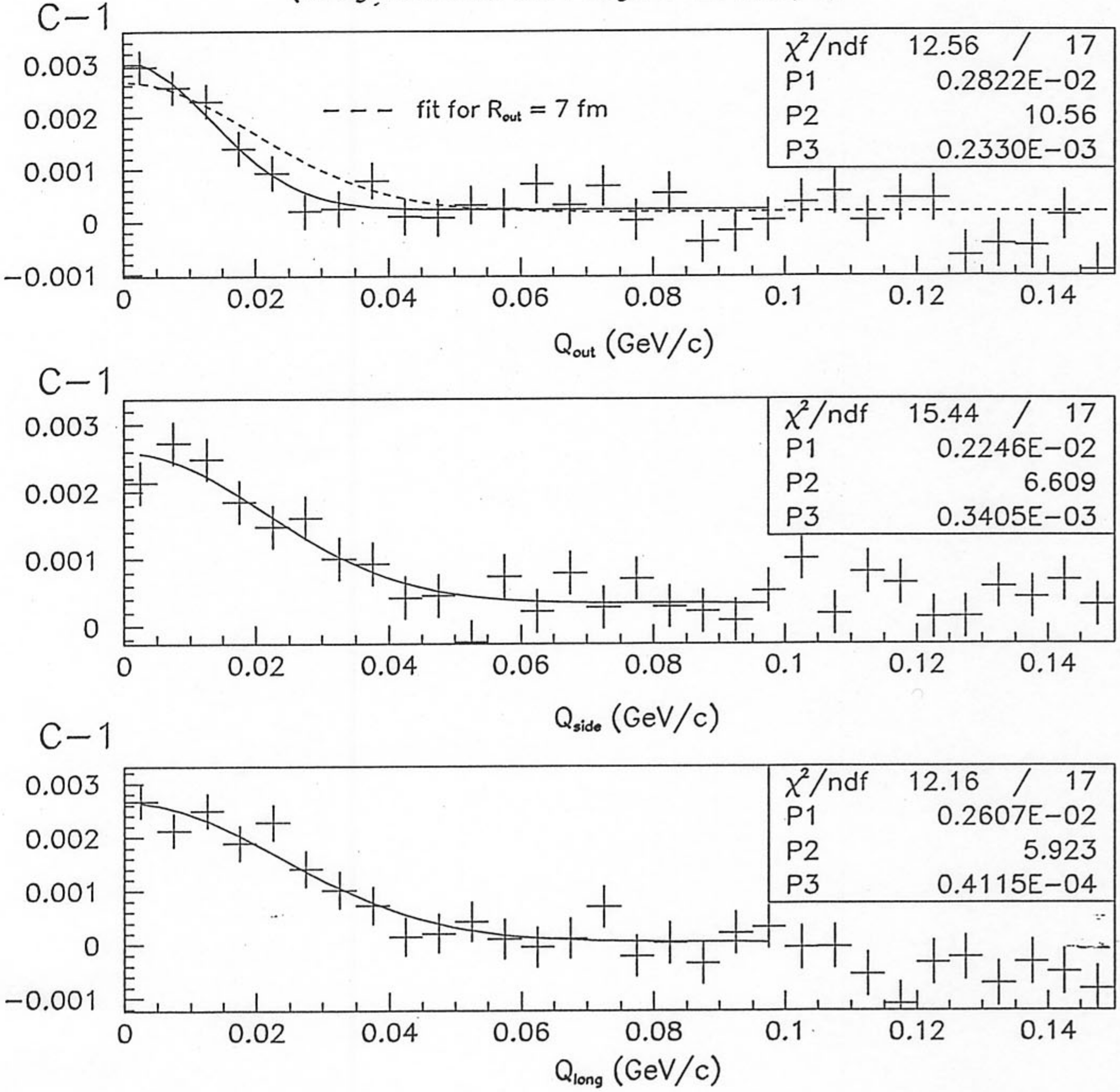
λ_{dir} taken $= 1$ (not .5)

so actual expt. will need

4 x statistics for same accuracy.

Direct γ generated with R_O, R_S, R_e (9, 7, 7) fm

Slices of 3d−correlation function
(integrated over the range 0−20 MeV/c)



RATES and RUNNING TIME

Need $\sim 10^9$ events (per Expt.)

RHIC II Luminosity $\sim$ 40,000 ev/s

$\Rightarrow$ 2000 central (5%) / s

Assume DAQ can do 1000 ev/s

Expt. Run Time $= \frac{10^9}{10^3} = 10^6 s = \underline{278 \text{ hrs}}$

This is a reasonable time BUT

points to the need for

FAST DAQ!

CONCLUSIONS

- Direct γ HBT opens a new window in the study of the QGP-
  IMPORTANT, UNIQUE, NEW PHYSICS

- These experiments CAN be done!

- A great physics opportunity would be lost if the direction chosen for the STAR upgrade R&D forclosed this possibility.

- This points very clearly in the direction of a new TPC + FAST DAQ!
  - along the direction of N. Smirnoff.
    (i.e. small, accurate, fast)

- Even if all γ detection is by the Calorimeter, we still need the TPC to find the vertex so the angular measurement of γ will be accurate enough for HBT.
  (The RHIC "diamond" will never be short enough to "define" the vertex to the necessary accuracy).

CONCLUSIONS (CONT'D)

- It should be noted that an experiment with γ detection and event sample size needed for direct γ HBT

  CAN PERFORM A LARGE VARIETY OF OTHER EXPERIMENTS

$$\eta' \to \eta + \pi^+ + \pi^-$$
$$\hookrightarrow \gamma + \gamma$$

$$\omega^0 \to \pi^+ + \pi^- + \pi^0$$

$$D^+ \to \overline{K}_0 + \pi^+ + \pi^0 \quad (9.7\%)$$

$$D_s^+ (\text{nee } F) \to \phi + \pi^+ + \pi^0 \quad (\sim 9\%)$$

(charmed, strange meson)

⋮